FILM MEASUREMENT WITH INTERLEAVED LASER CLEANING

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CLAIM OF PRIORITY

[0001]   This application claims priority to U.S. provisional application serial number 60/426,138, filed November 13, 2002 entitled "Film Measurement With Interleaved Laser Cleaning".

FIELD OF THE INVENTION

[0002]   This invention relates generally to measurement systems, and more particularly to a system and method for minimizing contamination effects on metrology operations.

BACKGROUND OF THE INVENTION

[0003]   As the dimensions of semiconductor devices continue to shrink, accurate and efficient characterization of the components forming those devices becomes more critical. Typically, the manufacturing process for modern semiconductor devices includes the formation of a number of layers or "thin films" on a silicon wafer. The thin films can include oxide, nitride, and/or metal layers, among others. To ensure proper performance of the finished semiconductor devices, the thickness and composition of each thin film formed during the manufacturing process must be tightly controlled.

[0004]   Modern thin films have reached the point where the accuracy and reproducibility of thin film metrology (i.e., measurement and/or inspection) can be limited by contamination on the surface of the thin film. For example, airborne molecular contamination (AMC) such as water and other vapors can be absorbed onto the thin film, creating a contaminant layer that adversely affects thin film analysis techniques such as optical

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ellipsometry, optical reflectometry, grazing-incidence x-ray reflectometry (GXR), x-ray fluorescence (XRF), electron microprobe analysis (EMP), and non-contact electrical analysis – all of which operate by directing a probe beam (optical, x-ray, electron or corona discharge) at the surface of the thin film to be measured. The contaminant layer can also interfere with measurements techniques that physically contact the surface of the thin film, such as contact-based electrical analysis (e.g., spreading resistance analysis).

[0005]   Conventional methods for cleaning thin films include heating the entire wafer in an oven to a temperature of about 300° C to vaporize any contaminant layer. Fig. 1a shows a conventional oven-based wafer cleaning system 100a used to prepare a wafer 110 for thin film analysis, as described in U.S. Patent No. 6,325,078, issued December 4, 2001 to Kamieniecki. Wafer 110 includes a thin film layer 112 formed on a silicon substrate 111, and a contaminant layer 113 formed on the surface of thin film layer 112. Wafer cleaning system 100a comprises a wafer stage 120 and multiple heat lamps 130. Wafer stage 120 positions wafer 110 under heat lamps 130, where thermal radiation from heat lamps 130 heats wafer 110 to vaporize contaminant layer 113. It is believed that this cleaning process is aided by optical photons from heat lamps 130 breaking bonds between contaminant layer 113 and thin film layer 112.

[0006]   Fig. 1b shows another conventional wafer cleaning system 100b used to prepare wafer 110 for thin film analysis, as described in U.S. Patent No. 6,261,853, issued July 17, 2001 to Howell et al. Just as described with respect to Fig. 1a, wafer 110 includes a thin film layer 112 formed on a silicon substrate 111 and a contaminant layer 113 formed on the surface of thin film layer 112. Cleaning system 100b incorporates a stage 140 that includes a heating element 141. Heat generated by heating

element 141 is conducted through stage 140 into wafer 110, thereby providing the heating required to vaporize contaminant layer 113. A heat exchanger can be coupled to stage 140 to capture excess heat from heating element 141 to minimize undesirable heating of cleaning system 100b itself and the surrounding environment.

[0007] Although wafer cleaning systems 100a and 100b use different thermal energy sources (i.e., heat lamps 130 and heating element 141, respectively), both systems perform a bulk heating operation to remove contaminant layer 113. The large thermal control components (e.g., lamps, heated stages, heat exchangers, etc.) typically used for bulk wafer heating undesirably increase the cleanroom space required for these conventional cleaning systems. Further exacerbating the problem of excess equipment size, conventional cleaning systems are sometimes stand-alone units used in conjunction with a thin film analysis tool. Therefore, conventional cleaning systems can significantly increase the total footprint required for a complete thin film analysis system. The use of a separate cleaning system also has an adverse effect on throughput, as time must be spent transferring the wafer to and from the cleaning system. In addition, contaminants can redeposit on the cleaned wafer while it is being transferred from the cleaning system to the film analysis tool.

[0008] In an attempt to somewhat alleviate these equipment size and recontamination problems, attempts have been made to combine wafer cleaning and measurement capabilities in a single tool. For example, the aforementioned U.S. Patent No. 6,261,853 describes integrating cleaning system 100b with an existing metrology tool (Opti-Probe 5240 from Therma-Wave, Inc.). Also, the Quantox XP tool from KLA-Tencor integrates a wafer cleaning system similar to cleaning system 100b with a non-contact

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electrical film measurement system. However, any bulk wafer heating system must still incorporate the aforementioned (large) thermal control components. Furthermore, even if a combined system is used, the bulk heating operation can significantly degrade overall wafer processing throughput. Several seconds are required to heat the wafer to the temperature required for removal of the contaminant layer, and another several seconds are required to cool down the wafer after cleaning. Any wafer handling operations that must be performed during and after the cleaning operation (e.g., transferring the wafer from the cleaning system to the thin film analysis system) further reduces the throughput. Note also that any delays after cleaning allow contaminant regrowth on the wafer.

[0009]   To improve throughput and reduce system footprint, a laser cleaning system can be incorporated into a metrology system. Fig. 2a shows an integrated laser cleaning metrology system 200, which is described in detail in co-owned and co-pending U.S. Patent Application Serial No. 10/056,271. Metrology system 200 comprises a stage 220, an energy beam source 230, and an analysis module 240. The compact components used in an energy-beam based cleaning system (such as energy beam source 230) can be efficiently integrated into metrology system 200 to minimize system footprint.

[0010]   Stage 220 holds a test sample 210 that comprises a thin film layer 212 formed on a substrate 211 and a contaminant layer 213 formed on the surface of thin film layer 212. Energy beam source 230 directs an energy beam 231 at a spot 214a on contaminant layer 213 to expose the underlying portion of thin film layer 212. Then in Fig. 2b, stage 220 positions test sample 210 under analysis module 240 so that a measurement beam 246 can be directed onto thin film layer 212 through an opening 214b formed by the laser heating of spot 214a during the preceding

cleaning operation (as shown in Fig. 2a). Since only a localized portion of contaminant layer 213 is cleaned, the long heating and cooling times associated with conventional cleaning systems can be avoided to improve throughput, and the only delay between cleaning and measurement is the time required to reposition test sample 210 under analysis subsystem 240 - typically 1-2 seconds.

[0011]   However, as metrology parameters become ever more sensitive to AMC, even this 1-2 second delay between cleaning and measurement can allow an excessive amount of AMC recontamination onto the thin film layer. For example, many modern metrology operations require test sample surface stabilities on the order of a tenth of an angstrom. However, AMC regrowth rates can be in the 1Å/sec range, in which case a repositioning delay of even a second can lead to significant measurement inaccuracies. Furthermore, since the measurement process itself can take a few seconds to complete, significant AMC regrowth can actually take place over the course of the measurement operation.

[0012]   Accordingly, it is desirable to provide a method and system for performing thin film metrology that avoids the aforementioned problems associated with AMC contamination and regrowth.

SUMMARY OF THE INVENTION

[0013]   The present invention provides a system and method for concurrent localized cleaning and analysis of a test sample to provide enhanced measurement accuracy. By performing a localized cleaning operation(s) during the actual analysis operation (i.e., "interleaving" cleaning and analysis operations), analysis degradation due to contaminant layer regrowth can be minimized. Furthermore, by eliminating the need for repositioning of the test sample between cleaning and analysis operations, throughput

is enhanced while the potential for misalignment (due to the repositioning operation) is reduced.

[0014]   A metrology system in accordance with an embodiment of the present invention comprises a cleaning subsystem, an analysis subsystem, a focusing subsystem, and a stage. The stage holds a test sample (such as a wafer) to be analyzed by the analysis subsystem. The analysis subsystem can comprise any metrology system or systems, including an ellipsometry system, such as a single-wavelength ellipsometry system (SWE) or a spectroscopic ellipsometry system (SE), a reflectometry system, a contact-based electrical measurement system, a non-contact electrical measurement system, a GXR system, an XRF system, an EMP system, and/or a scanning electron microscope (SEM) inspection or review system. More generally, the cleaning subsystem can be integrated with any sort of measurement system, such as metrology systems used in the production of semiconductor devices.

[0015]   The focusing subsystem positions the analysis subsystem and the cleaning subsystem relative to the stage such that a measurement beam (or probe) from the analysis subsystem and a pulsed cleaning beam generated by the cleaning subsystem are simultaneously focused on the test sample. According to an embodiment of the invention, the analysis subsystem includes a measurement emitter for generating and directing the measurement beam at a analysis location, and also includes a measurement receiver for measuring the output beam(s) generated from (i.e., reflected by, emitted from, scattered by, etc.) the analysis location in response to the measurement beam so that the test sample can be analyzed. The cleaning subsystem includes a cleaning beam emitter for generating and directing the cleaning beam at the same analysis location. By performing a cleaning operation during the analysis operation, the cleaning system

minimizes contaminant regrowth and provides a stable analysis environment for the analysis subsystem.

[0016]   According to an embodiment of the invention, the cleaning beam can comprise a series of cleaning pulses, i.e., a series of on/off states. This in turn helps to minimize any effect the cleaning operation might have on the measurement operation. Depending on the characteristics of the pulsed cleaning beam, the pulse (on) portions may introduce local effects that could affect the measurements being taken by the analysis subsystem (of course, the non-pulse (off) portions of the pulsed cleaning beam will have no effect on the measurements). For example, each pulse of a laser cleaning beam could cause localized heating of the test sample that could in turn affect measurements taken at this elevated temperature.

[0017]   Depending on the specific cleaning effects and the sensitivity of the analysis subsystem to those effects, various approaches can be taken to minimize their impact. According to an embodiment of the invention, if the cleaning effects are small enough, they can simply be ignored. According to another embodiment of the invention, the width (i.e., the duration of the pulse) and period (i.e., the time between the start of one pulse and the next) of the cleaning pulses in the pulsed cleaning beam could be timed to fall between measurement samples taken by the measurement subsystem. According to another embodiment of the invention, the analysis subsystem can include a clamp circuit that clamps measurement samples taken during each cleaning pulse (and during the cooldown period after each cleaning pulse) at the level of a measurement sample just before the cleaning pulse. According to another embodiment of the invention, post-processing can be performed on the sampled data to delete or replace measurement samples taken during each cleaning pulse and associated cooling period.

[0018]   The present invention will be more fully understood in view of the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019]   These and other features, aspects and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings.

[0020]   Figs. 1a and 1b are schematic diagrams of conventional wafer cleaning systems.

[0021]   Figs. 2a and 2b are schematic diagrams of another wafer cleaning system.

[0022]   Figs. 3a, 3b, 3c and 3d are schematic diagrams of a metrology system including interleaved cleaning capability in accordance with an embodiment of the invention.

[0023]   Fig. 4 is a beam diagram showing localized cleaning and measurement in accordance with an embodiment of the invention.

[0024]   Fig. 5 is a plan view of the metrology system of Figs. 3a-3c in accordance with an embodiment of the invention.

[0025]   Figs. 6a, 6b, and 6c are graphs comparing sampling rate with cleaning pulses and cleaning effects according to an embodiment of the invention.

[0026]   Fig. 7 is a schematic diagram of a clamping circuit according to an embodiment of the invention.

DETAILED DESCRIPTION

[0027]   Fig. 3a shows a metrology system 300 that includes interleaved cleaning capability in accordance with an embodiment of the invention. Metrology system 300 includes a stage 320, an analysis subsystem 330, a cleaning subsystem 360, and a focusing subsystem 370. Stage 320 holds a test sample 310 that comprises a thin film layer 312 formed on a substrate 311. Substrate 311

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can comprise any structure on which thin film layer 312 can be formed, including a single-layer structure (such as a silicon wafer) or a multi-layer structure (such as an additional thin film layer or layers formed on a silicon wafer). Test sample 310 also includes a contaminant layer 313 formed on the surface of thin film layer 312. Contaminant layer 313 can comprise any unwanted material, such as AMC, on the surface of thin film layer 312. Note that while contaminant layer 313 is shown covering the entire surface of thin film layer 312 for explanatory purposes, contaminant layer 313 can also only partially cover thin film layer 312.

[0028]   To perform a metrology operation, an alignment operation is first performed using focusing subsystem 370 to properly align analysis subsystem 330 and cleaning subsystem 360 with test sample 310. According to an embodiment of the invention, focusing subsystem 370 includes a focusing emitter 380 and a focusing receiver 390. For explanatory purposes, focusing emitter 380 is shown comprising an alignment beam source 381, a protective filter 382, directional optics 383, and a lens 384, while focusing receiver 390 is shown comprising a position-sensitive detector 391, a protective filter 392, directional optics 393, and a lens 394. However, focusing emitter 380 and focusing receiver 390 can comprise any components that are capable of providing the desired focusing performance.

[0029]   To perform a focusing operation, alignment beam source 381 generates an alignment beam 375. According to an embodiment of the invention, alignment beam source 381 can comprise various light sources, including white-light lamps, such as xenon discharge lamps or tungsten halogen lamps, light-emitting diodes (LEDs), or near-infrared (NIR) lasers. Alignment beam 375 passes through protective filter 382 and is guided by directional optics 383 through a lens 384 that focuses alignment beam 375 onto an

analysis location 314. Alignment beam 375 penetrates contaminant layer 313, which is very thin and therefore has a negligible effect on the focusing operation. A resulting reflected alignment beam 376 is then focused by lens 394 and directed by directional optics 393 through protective filter 392 onto position sensitive detector 391. Position sensitive detector 391 measures the positional characteristics of reflected alignment beam 376, from which an accurate position for test sample 310 can be trigonometrically determined. Protective filters 382 and 392 prevent stray light (e.g., ambient light, measurement or cleaning light, etc.) from damaging or interfering with the measurements of focusing subsystem 370. For example, if alignment beam source 381 is a white-light lamp or a NIR laser, protective filters 382 and 392 can comprise NIR filters (i.e., filters that only pass NIR light).

[0030] Once the position of test sample 310 is known, the position of analysis subsystem 330 can be adjusted relative to stage 320 via an optional adjustment mechanism 331 in analysis subsystem 330 and/or an optional adjustment mechanism 321 in stage 320. This positioning operation ensures that a measurement beam generated by analysis subsystem 330 (discussed below with respect to Fig. 3d) is properly focused on test sample 310. An adjustment mechanism 361 in cleaning subsystem 360 is likewise used to position cleaning subsystem 360 relative to stage 320 to ensure that a cleaning beam generated by cleaning subsystem 360 (discussed below with respect to Fig. 3b) is properly focused on test sample 310.

[0031] Once the alignment operation is completed, an initial cleaning operation can be performed by cleaning subsystem 360 to place analysis location 314 in the desired condition for metrology by cleaning away the overlying portion of contaminant layer 313. As shown in Fig. 3b, according to an embodiment of

the invention, cleaning subsystem 360 includes a cleaning beam emitter 362 that directs a cleaning beam 366 at analysis location 314 on test sample 310. For explanatory purposes, cleaning beam emitter 362 includes a cleaning beam source 363, directional optics 364, and a lens 365. However, cleaning beam emitter can comprise any components capable of providing the desired cleaning functionality.

[0032]   Cleaning beam source 363 generates cleaning beam 366, which is then guided by directional optics 364 through lens 365, which focuses cleaning beam 366 onto analysis location 314. Cleaning beam 366 is configured to remove enough of contaminant layer 313 to reveal analysis location 314 of thin film layer 312. This removal process can comprise either an interaction with contaminant layer 313 and/or an interaction with the underlying portion(s) of thin film layer 312 and/or substrate 311. For example, cleaning beam 366 could comprise a laser tuned to heat contaminant layer 313 directly or heat the underlying portion of thin film layer 312 or substrate 311. Note that the specific contaminant layer removal mechanism will depend on the type of cleaning beam used.

[0033]   Cleaning subsystem 360 and focusing subsystem 370 can share a common optical path to optimize layout efficiency and permit the sharing of focusing optics to reduce system cost. Fig. 3c shows a metrology system 300-1 that includes interleaved cleaning capabilities in accordance with another embodiment of the invention. Metrology system 300-1 is substantially similar to metrology system 300 shown in Figs. 3a and 3b, except that focusing receiver 390 and cleaning beam emitter 362 share a common lens 395 for focusing reflected alignment beam 376 onto position sensitive detector 391 and for focusing cleaning beam 366 onto analysis location 314, respectively. Because they use lens 395, reflected alignment beam 376 and cleaning beam 366

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share a common optical path (i.e., are aligned) between lens 395 and analysis location 314 of test sample 310. A dichroic mirror 394 reflects cleaning beam 366 and transmits reflected alignment beam 376, thereby placing the two beams in alignment. As noted above, position sensitive detector 391 and alignment beam source 381 are protected from scattered cleaning light by protective filters 392 and 382, respectively.

[0034]   During cleaning operations, the potential for damage to the underlying thin film layer 312 and/or substrate 311 during the cleaning process is minimal because of the localized action of cleaning beam 366. Furthermore, the fact that cleaning and measurement are interleaved in time allows a lower cleaning beam power to be used than is the case where cleaning and measurement are separated in space and time (i.e., where cleaning intervals are much greater). This lower cleaning beam power also serves to reduce the possibility of damage to the sample. The risk of damage can be further reduced by performing the cleaning operation on non-functional regions of test sample 310 (e.g., regions such as scribe lines that will not be part of the functional portion(s) of the final devices to be made from test sample 310).

[0035]   To minimize the effect of the interleaved cleaning process on the beam characteristic measurements being taken by metrology system 300, cleaning beam emitter 362 shown in Fig. 3b can provide cleaning beam 366 as a pulsed beam. According to an embodiment of the present invention, cleaning beam source 363 could comprise a pulsed laser. For example, contaminant layer 313 could comprise a 5 angstrom thick layer of water and organic materials (which is similar to contamination layers often formed on modern thin film layers during production). A number of pulses or even a single pulse from a 5-100μJoule laser having a 1-1000ns pulse duration could then heat the desired portion of

contaminant layer 313 to between roughly 300°C to 1000°C, which is a temperature range sufficient to vaporize that portion of contaminant layer 313.

[0036]   According to another embodiment of the invention, cleaning beam source 363 could comprise a Q-switched laser delivering a relatively high peak power, such as a frequency-doubled or tripled YAG (yttrium aluminum garnet) laser operating at wavelengths of 532nm or 355nm, respectively. According to another embodiment of the invention, other types of pulsed lasers operating at different wavelengths might be used including pulsed diode or alexandrite lasers.

[0037]   According to another embodiment of the invention, a continuous laser, such as an argon-ion laser, could be externally modulated (such as with an acousto-optic or electro-optic modulator) to produce pulses. According to another embodiment of the invention, cleaning beam source 363 could comprise a flashlamp coupled to focusing optics to direct the high intensity light to the desired area on contaminant layer 313. According to other embodiments of the invention, cleaning beam emitter 362 can comprise a pulsed microwave source, a pulsed gas jet source, a pulsed acoustic source, a pulsed dry ice jet, or a pulsed ion beam source.

[0038]   To provide the desired amount of initial cleaning, cleaning subsystem 360 can apply cleaning beam 366 to analysis location 314 until a predefined number of pulses have been applied to the region. Note that the duration and/or period of the cleaning pulses in cleaning beam 366 during this initial cleaning process do not necessarily have to be the same as the duration and/or period of the cleaning pulses used for the interleaved cleaning operation (i.e., the cleaning operation performed concurrently with the measurement operation). The cleaning pulses of cleaning beam 366 form an opening 315 in

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contaminant layer 313, as shown in Fig. 3d, through which the actual measurement operation can them be performed.

[0039]   For explanatory purposes, measurement subsystem 330 is shown in Fig. 3d as comprising a measurement emitter 340 and a measurement receiver 350, and an optional computer 359. Measurement emitter includes a measurement beam source 341, an optional acousto-optical modulator 342, directional optics 343, a polarizer 344, a focusing lens 345 and a rotating waveplate 346. Measurement receiver 350 includes a detector circuit 351, an interference filter 352, a polarizer 353, a focusing lens 354, and a rotating waveplate 355. Therefore, measurement subsystem 330 as shown in Fig. 3d includes components for performing single wavelength ellipsometry (SWE), such as described in co-owned, co-pending U.S. Patent Application No. 09/298,007, herein incorporated by reference. Note, however, that as mentioned above, analysis subsystem 330 can comprise any type of analytical assembly, including spectroscopic ellipsometry (SE, such as described in co-owned U.S. Patent No. 5,608,526, herein incorporated by reference), reflectometry (optical or x-ray, such as described in co-owned U.S. Patent No. 5,747,813, herein incorporated by reference, or GXR, such as described in co-owned, co-pending U.S. Patent Application [Attorney Docket KLA-001], herein incorporated by reference), non-contact electrical analysis (such as described in co-owned U.S. Patent No. 5,485,091, herein incorporated by reference), XRF, EMP, SEM inspection/review, or contact-based electrical analysis (e.g., spreading resistance analysis), among others.

[0040]   To perform an SWE measurement process, measurement beam source 341 generates a measurement beam 335. According to an embodiment of the invention, measurement beam source 341 can comprise a helium-neon (HeNe) laser with a wavelength of 633nm. Optional acousto-optical modulator 342 can then be used to pulse

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measurement beam 335 if desired. Directional optics 343 direct
measurement beam 335 through polarizer 344 and then through
focusing lens 345. Passing through rotating waveplate 346,
measurement beam 335 has its polarization continuously modulated
from circular to linear and back again and directed onto the
portion of thin film layer 312 exposed through opening 315 in
contaminant layer 313 (i.e., analysis location 314). In response
to measurement beam 335, an output beam 336 is generated from (in
this case reflected by) analysis location 314. Note that
depending on the specific measurement process being used, output
beam 336 can comprise a single beam (e.g., if the measurement
process comprises ellipsometry) or multiple beams (e.g., if the
measurement process comprises XRF). Output beam 336 passes
through rotating waveplate 355, focusing lens 354, polarizer 353,
and interference filter 352 before striking detector circuit 351
(typically a photodiode circuit). Detector circuit 351 measures
the resulting intensity profile as a function of time to allow
calculation of the desired thin film characteristics – for
example, by optional computer 359.

[0041]   To ensure that accurate measurements are taken by
measurement subsystem 330, measurement beam 335 must have clear
access to analysis location 314. Accordingly, the specific
amount of contaminant layer 313 to be removed by cleaning beam
366 depends on the beam characteristics of measurement beam 335
(and the measurement characteristics of measurement subsystem
330). Modern thin film analysis tools generally require an
analysis area of at least 20μm x 20μm. Accordingly, at least a
20μm x 20μm portion of contaminant layer 313 would need to be
removed for such systems. However, to ensure that the entire
analysis area is uniformly cleaned, a larger portion of
contaminant layer 313 could be removed. Fig. 4 shows a detail
view of the portion of test sample 310 around analysis location

314, showing relative sizes of a cleaning beam spot 467 (through contaminant layer 313) produced by cleaning beam 366 and a measurement beam spot 437 (on thin film layer 312) produced by measurement beam 335, according to an embodiment of the invention. By focusing measurement beam 335 down to a smaller spot size (at analysis location 314) than the spot size of cleaning beam 366, greater tolerance for x-y alignment between alignment subsystem 330 and cleaning subsystem 360 (shown in Fig. 3b) is provided.

[0042]   Note that while Fig. 3a-3d show measurement subsystem 330, cleaning subsystem 360, and focusing subsystem 370 in a "stacked" configuration for explanatory purposes, the subsystems can take any desired arrangement. For example, Fig. 5 shows a plan view of metrology system 300 in accordance with an embodiment of the invention. While cleaning subsystem 360 remains aligned with focusing subsystem 370, measurement subsystem 330 is oriented perpendicular to focusing subsystem 370, such that the plan view directional component (i.e., parallel to the surface of test sample 310) of measurement beam 335 is perpendicular to the plan view directional components of cleaning beam 366 and alignment beam 375 (note that other non-parallel arrangements could also be implemented). This perpendicular arrangement can allow measurement subsystem 330 and focusing subsystem 340 to be more efficiently packed into metrology system 330.

[0043]   The concurrent application of cleaning beam 366 to analysis location 314 during the measurement process clears away any regrowth of contaminant layer 313 in opening 315 that would otherwise compromise the accuracy of the measurement data. However, depending on the characteristics of cleaning beam 366, the individual cleaning pulses of the beam may or may not introduce some inaccuracy into the measurements taken by

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measurement subsystem 330 by disturbing the test sample away from an analysis baseline condition. For example, if cleaning beam 366 comprises laser pulses for vaporizing AMC on the surface of test sample 310, localized heating produced by those laser pulses may affect measurement accuracy. Also, the cleaning beam may cause an excess of charge carriers in and around analysis location 314 that can affect the metrology operation and produce erroneous results. Other cleaning effects may induce similar disturbances. According to an embodiment of the invention, because the recovery period from disturbances caused by such "cleaning effects" is typically much shorter than the time required for significant AMC regrowth, cleaning effects can simply be ignored; i.e., any measurement inaccuracy due to the cleaning beam will simply be accepted.

[0044]   According to other embodiments of the invention, the cleaning effects can be compensated for in various ways, such as properly setting cleaning pulse timing, adjusting the measurement sampling characteristics, or selectively processing the raw data measurements. According to an embodiment of the invention, implementation of any of these compensation techniques can be simplified by setting the cleaning pulse rate (i.e., the number of cleaning pulses per unit time) of cleaning beam 366 equal to a submultiple of the sampling rate of measurement system 330, in which case cleaning beam 366 would introduce a substantially constant cleaning effect at constant intervals.

[0045]   Fig. 6a shows an example sampling rate graph for detector circuit 351 of measurement subsystem 330 shown in Fig. 3d. The data sampling begins at a time t0, and has a sampling period Ps (i.e., the time between the start of one sampling pulse and the start of the next sampling pulse; equal to 1/sampling rate) and sample width Ws (i.e., the duration of a sampling pulse). Nine samples are shown, taken at times t0-t8 (although

any number of samples can be taken). Fig. 6b shows an example cleaning pulse graph for cleaning beam 366 of cleaning subsystem 360 (shown in Fig. 3d) that could be used in conjunction with the sampling rate profile shown in Fig. 6a. Prior to time t0 (i.e., prior to the start of data sampling), a quantity of cleaning pulses having an intensity IN', widths Wc' and a period Pc' are applied to the test sample beginning at time t0' to perform the initial cleaning operation described with respect to Fig. 3b. Once data sampling has begun (i.e., after time T0), cleaning pulses are applied having an intensity IN, widths Wc and period Pc. Note that cleaning pulse intensity IN, width Wc, and period Pc can be different from cleaning pulse intensity IN', width Wc' and period Pc'; respectively. For example, to reduce the time required for the initial cleaning operation, cleaning pulse width Wc' can be set larger than cleaning pulse width Wc and/or period Pc' can be set shorter than period Pc.

[0046]   Fig. 6c shows a possible temperature profile for test sample 310 shown in Fig. 3d when subjected to cleaning beam 366 having the cleaning pulse profile shown in Fig. 6b. Each cleaning pulse shown results in a corresponding temperature spike – i.e., cleaning pulses at times tc1, tc2, and tc3 shown in Fig. 6b, produce corresponding temperature spikes at the same times in Fig. 6c. As indicated, the local temperature of the test sample rises from a steady-state temperature Tss to an elevated temperature Tel. Because the analysis location is generally a small portion of a much larger test sample, any heating from a cleaning pulse is rapidly dissipated, hence the narrow widths of the temperature spikes shown in Fig. 3c. For example, in a silicon wafer, the temperature spike from a 60ns cleaning pulse from a 532nm laser will have a width on the order of 1µs.

[0047]   According to an embodiment of the invention, by timing the cleaning pulses to fall between data samples, the temperature

disturbances caused by the cleaning pulses have time to dissipate and therefore not affect the actual measurements. By setting the cleaning pulses to occur immediately after the completion of a data sample, the allowable recovery period (cooling time) for that cleaning pulse can be maximized. For example, time tc1 of Fig. 6b could be set equal to time t2 of Fig. 6a added to sample width Ws. Similarly, time tc2 could be set equal to time t5 added to sample width Ws and time tc3 could be set equal to time t8 added to sample width Ws.

[0048]   Note that even if some portion of cleaning-induced temperature effects "bleeds" into some of the data samples, by averaging multiple samples to obtain final measurements, such transient heating effects will be "smoothed out". This smoothing effect can be enhanced by increasing the sampling rate of the detection circuit (e.g., photodiode detection circuit 351 shown in Fig. 3d). However, the higher the sampling rate of the detector, the more susceptible the detector becomes to high frequency noise.

[0049]   To avoid the problem of high frequency noise, a metrology system in accordance with another embodiment of the invention includes a low-bandwidth measurement receiver coupled with a measurement emitter that includes a modulator for the measurement beam (e.g., acousto-optical modulator 342 shown in Fig. 3d). Then, a high-frequency modulated measurement beam can be used to provide the desired high sampling rate, while the low bandwidth detector minimizes the problem of high-frequency noise. The modulator blocks the measurement beam during the cleaning pulse and any subsequent cooling period so that no information from the sample is received during cleaning (and cooling) operations. The modulator can also block the measurement beam between sampling pulses to avoid introducing artifacts at the cleaning laser pulse rate. Blocking the measurement laser between

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each sampling pulse would introduce a known, fixed artifact at the sampling rate that can be accounted for in downstream processing, thereby effectively making each inter-sampling interval identical, whether or not a cleaning pulse occurs.

[0050]   According to another embodiment of the invention, the detection circuit includes a clamp circuit to blank out any information received from the sample during cleaning pulses (and any subsequent recovery period). Fig. 7 shows a photodiode detector circuit 700 in accordance with an embodiment of the invention. Photodiode detector circuit 700 includes a photodiode PD, an amplifier circuit 702, and a clamp circuit 710. Amplifier circuit 702 comprises an op-amp 701, a resistor R, and a capacitor C. Photodiode PD is connected to the negative input terminal of op-amp 701, and resistor R and capacitor C are connected in parallel across the negative and output terminals of op-amp 701 to control the time constant (and therefore the bandwidth) of the amplifier circuit. Clamp circuit 710 includes a sample/hold circuit 720, a low-pass filter 730, an analog-to-digital (A/D) converter 740, and a control circuit 750. Note that the bandwidth of amplifier circuit 702 should be greater than the sampling rate of A/D converter 740 to ensure that raw data Draw always provides a valid data signal to sample/hold circuit 720.

[0051]   Sample/hold circuit 720 is coupled to receive raw data Draw from op-amp 701 and a control signal CLAMP from control circuit 750. During non-cleaning periods of operation, sample/hold circuit passes raw data Draw as processed data Dpro to low-pass filter 730, which in turn filters out any high frequency noise and passes filtered data Dfil to A/D converter 740, which samples filtered data Dfil to generate final output data Dout. However, during cleaning operations (and any subsequent recovery periods), control circuit 750 asserts control

signal CLAMP, which places sample/hold circuit 720 into hold mode. This causes sample/hold circuit 720 to set processed data Dpro to the level of raw sample data Draw just prior to the start of the cleaning operation and hold processed data Dpro at that level until after the cleaning and recovery period has passed.

[0052]   According to another embodiment of the invention, data processing software in optional computer 359 shown in Fig. 3d can be used to delete data samples taken during cleaning operations and any subsequent recovery periods. This data deletion will generally not be problematic since the data is typically highly oversampled. According to another embodiment of the invention, the data processing software could replace the deleted data samples with data equal to the last data sample taken before the start of the cleaning operation.

[0053]   According to another embodiment of the invention, measurement subsystem 330 shown in Fig. 3b comprises a spectroscopic ellipsometry (SE) measurement system, in which rotating waveplates 346 and 355 are not present, and polarizer 353 comprises a rotating analyzer. In an SE measurement system, the intensity of output beam 336 is low, so that any measurements of this beam must be integrated over many milliseconds by detector circuit 351 before being read out. At least eight such integrations ("readout cycles") must be performed during one rotation of polarizer 353. According to an embodiment of the invention, the cleaning pulses in cleaning beam 366 can be synchronized with the readout timing of detector circuit 351 so that there are a constant integer number of cleaning pulses per readout cycle. The transient perturbations caused by the cleaning pulses are then accepted and taken to be constant. According to another embodiment of the invention, measurement beam source 341 can be a broadband flashlamp or pulsed plasma source that fires at a predetermined rate, and the cleaning

pulses of cleaning beam 366 are timed to fall between firings such that any disturbances such as temperature spikes are allowed to dissipate before the next measurement is taken.

[0054]   The various embodiments of the structures and methods of this invention that are described above are illustrative only of the principles of this invention and are not intended to limit the scope of the invention to the particular embodiments described.   Thus, the invention is limited only by the following claims and their equivalents.